

Photochemical Behavior of Wood Based Materials

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Abstract Wood, as a natural composite material used mainly in exterior construction and building applications, requires long-term durability under exposure to environmental factors including solar UV radiation, temperature, humidity and pollutants. The outdoor service life of wood and wood based materials, namely wood thermoplastic polymer composites, is strongly related to their deterioration under weathering conditions. Wood is extremely sensitive to UV radiation in the range from 300 to 400 nm. Photo-chemical degradation of wood causes significant structural and color changes, lignin component being the most susceptible to de-polymerization reactions by which phenoxy radicals are generated as intermediates and further oxidized into colored chromophores (quinones). Effective treatments, e.g. UV photo-stabilizers, or surface coatings of wood products, e.g. paints, varnishes, stains or water repellents, may provide significant wood protection against weathering in long-term outdoor applications.

1 Introduction

Polymer based materials (wood, plastics) used in the exterior of buildings and in construction have a service life determined by their exposure to UV radiation from sunlight and consequently their further deterioration through weathering process. Both climate changes which determine a substantial temperature increment, as well as increasing of the UV radiation levels, mainly UV-B radiation component, cause a significant diminution of service life for such materials in outdoor applications.

Dedicated to the memory of my dear friend and colleague, Dr. Ruxanda Bodîrlu, who recently passed away.

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Through appropriate stabilization methodologies, e.g. modification of polymer properties and use of high quality light stabilizers, the mitigation of deleterious effects induced by increased UV radiation levels upon polymer materials can be attained with maintenance of their lifetime under outdoor exposure conditions [1].

Investigation and knowledge of wood aging and its properties changes are of great significance for conservation of cultural heritage objects and historic buildings made from wood and also for the restoration of ancient wood constructions. In this context, a recently thorough literature review presents the different aspects of wood aging [2]. A new methodology using Fourier transform infrared spectroscopy (FTIR) in order to study the age of the carving phase for wood objects can be effectively applied, with analysis of samples from different depths and localizations for an eventual gradient of water absorbed (namely, hydroxyl groups OH) between the surface and the inner part of both an ancient and a modern wood sculptures [3].

The commercial value and the usage of the wood is strongly related to the colour changes caused by UV radiation on the surface, these further affecting wood's esthetical appearance and its entire properties (e.g. physical, mechanical). The colour changes may be correlated and validated by statistical analysis with chemical changes evidenced in wood structure after photo-degradation process through spectral analysis, an effective method to estimate the preservation stage for the wood surfaces [4].

Wood is a natural composite material consisting of different polymers, including polysaccharides, namely cellulose and hemicelluloses, and an amorphous three-dimensional network polymer comprising different linked phenyl-propane units, namely lignin, which act as binder in wood composite structure, and extractives (Fig. 1).

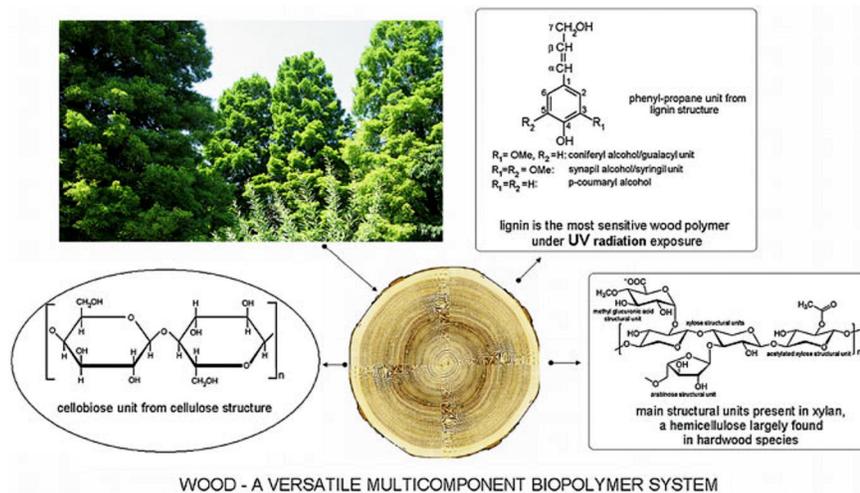


Fig. 1 Schematic representation of wood chemical structure

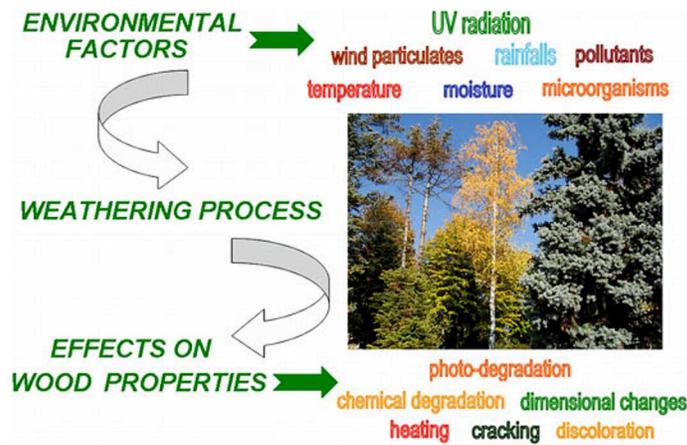


Fig. 2 Schematic representation of wood weathering process under environmental factors action

Wood is the most versatile and widely exploited engineering material for both indoor and outdoor applications, mainly in building constructions. Wood has many advantages including aesthetic appearance, easy processing, low density, low thermal expansion, and good mechanical properties. Wood and wood based materials (e.g. polymer composites) are susceptible to undergo surface degradation processes, mainly under exposure to outdoor environmental conditions which involve a complex combination of chemical, mechanical and light factors. These include: solar radiation mainly UV part; winds; particulates; humidity occurred through dewing, raining, and snowing; temperature; atmospheric oxygen; pollutant gases such as sulphur dioxide, and nitrogen dioxide. All of these factors significantly contribute to the *weathering process* [5-9]. A schematic representation of this process is presented in Fig. 2.

Wood interacts with the electromagnetic spectrum of sunlight, namely ultraviolet (UV) radiation, being a very good light absorber, and further determines photochemical reactions (photolysis, photo-oxidation, and thermal oxidation) in the weathering or oxidative degradation processes of wood [5, 8, 10-12]. Usually, this very complex process relies upon activation of the chromophore groups which in the case of wood and wood based materials are represented by the phenolic groups commonly present in lignin biopolymer from wood structure. Among constituent wood biopolymers, lignin is the most reactive through its chromophore groups which are the most sensitive under sunlight exposure, especially UV radiation [13-16]. It is also well-known that the presence of extractives, mainly phenolic type ones, strongly influences the photo-degradation process, these kinds of compounds being very sensitive to the UV light action [17, 18]. These chromophores generate free radicals through chains cleavage with occurrence of low molecular weight compounds which are yellow coloured, mainly quinones, and stilbenes [19]. The colour changes are also determined by occurrence of carbonyl groups through

photo-degradation process [15]. These substances represent a good substrate for the fungal growth (blue staining fungi) that further initiates biodegradation thus increasing wood deterioration on its surface and even causing entire structure destruction. Usually, a roughened texture and cracks on the wood surfaces followed the combined action of the UV radiation from sunlight and water from rainfalls [7, 8, 20]. This rapid degradation affects to a large extent the mechanical behaviour of wood under outdoor exposure conditions, thus limiting its service life. That is why it is very important to control the UV light impact upon wood surfaces [10].

Physical degradation features of wood surface include bleaching (usually called discoloration), micro-structure checking, and erosion on the top surface (evidenced through enhanced roughness, loss of gloss and lightness) which are readily observed under visual investigation. The occurrence of chemical changes in wood structure is mainly evidenced through colour changes with the progress of the weathering process [16, 21–24]. Further, significant deleterious effects upon wood's aesthetic value and performance can be observed, wood being subjected to a more enhanced and progressive photo-oxidative degradation process.

2 Photochemical Behaviour of Wood Based Materials

Conversion of matter (organic, inorganic) implies occurrence of ageing and deterioration processes of materials. Weathering is the dominant process of natural ageing caused by abiotic and biotic factors mainly when inorganic materials are involved. This process implies chemical transformation by changing the original state, this meaning not only degradation but also occurrence of new compounds and even their desirable stabilization. In this context, the multivariate data analysis can be an effective tool to indicate the contribution of different environmental factors [25].

Modification of biopolymers (e.g. wood or cellulose component) through different chemical and physical routes is usually applied for increasing to some extent their resistance against biological degradation caused by microbial communities. Wood modification through chemical reactions including esterification (using organic anhydrides, e.g. acetic, succinic, or aromatic vinyl esters), or reaction of wood with furfuryl alcohol, and resins treatment, or physical treatments (e.g. thermal, plasma) can contribute to an increased lifetime of wood based materials and products by improving the resistance of wood to photo-degradation [13, 26–29]. However, these structural diversification routes generate some problems related to the environmental degradation of the resulted modified wood materials.

The degradation processes of plastics, rubber and wood materials are oxidative reactions which are accelerated under exposure to increased levels of UV radiation (especially UV-B component 280–315 nm that is efficiently absorbed by chromophores present in these materials), mainly at high ambient temperatures (thermal oxidation). As immediate consequences, useful service life-time periods for such materials in outdoor applications are significantly reduced [10, 30, 31].

Chemical additives are usually used for light-stabilization of plastic materials, while UV resistant coatings (e.g. clear polyurethane coatings) are applied for wood products protection, since photo-degradation processes cause increased water sensitivity and further their biodegradation under outdoor exposure conditions [32]. In most cases, it is preferable to use materials with greater resistance to UV radiation in order to prevent the increased damage of these materials under outdoor exposure to solar radiation.

The technical advances in degradation and stabilization techniques which impact the lifetimes of plastics and wood products routinely exposed to solar UV radiation and the protection to humans offered by materials against solar UV radiation were recently assessed [1].

Photo-degradation process in wood and wood-based materials is usually limited to the surface layer, this being the location for many phenomena including physical and chemical interactions between a material and its surrounding environment. Nevertheless, the process is strongly related to the depth of penetration of the UV radiation. Therefore, accelerated testing of wood in laboratory conditions requires use of UV light sources that generate similar depths of penetration as resulted in natural conditions [10].

The exposure of wood to indoor and especially outdoor conditions (namely moisture, sunlight radiation, heat/cold, wind abrasion, biological agents which exert their action as individual or in combination) significantly affects its native durability (dimensional stability, surface integrity), thus occurring natural degradation process [5, 7, 8, 33].

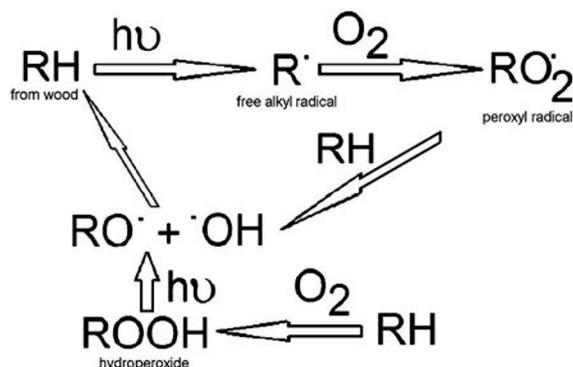
Wood weathering is initiated primarily by solar radiation, mainly the UV portion of the solar spectrum. It can be considered as a photo-oxidation or photo-chemical process that starts immediately after wood exposure to sunlight action, affecting only the surface of the wood. Initially, the colour changes occur and these are visually noticeable, further a slow erosion process being induced and accompanied by increased loss of the surface wood fibers [7, 8]. The main features of the weathering process are strongly influenced and determined by the wood properties including density (one of the most important factors affecting the process), grain characteristics (presence of early wood and latewood), texture (hardwood or softwood species), extractives, resins, and oils content [7].

Investigation related to the photo-degradation process of wood under UV radiation exposure was initiated some decades ago [12, 34]. This type of investigation implies usually two distinct stages, as follows:

1. *irradiation* of wood surface using different UV light sources;
2. *monitoring* and evaluation of the changes (structural, colour, morphological) occurred under UV radiation exposure.

The absorption of UV light by wood occurs mainly due to the absorption by lignin (an aromatic polymer wood component) that is a good absorber of UV radiation comparatively with cellulose (the main polysaccharide from wood structure). It seems that lignin acts as a photo-sensitizer in the degradation of the

Fig. 3 Schematic representation of photo-oxidative pathway during photo-degradation process



other wood components by transferring light energy [12]. After absorption of a quantum of energy $h\nu$ (photon) by wood, the occurrence of the free radicals through main chain scission (dissociation of chemical bonds) is observed, these resulted radicals being easily detected using electron spin resonance (ESR) method [8].

Among the intermediate products formed, there are mainly those containing oxygen with low activation energy, namely peroxides, hydroperoxides, peroxy, and alkoxy radicals (schematically presented in Fig. 3), these being involved into further chemical and photo-chemical reactions.

Alkoxy radicals (RO^\bullet) are well-known as intermediate products involved in the pyrolysis and photolysis reactions of organic compounds (peroxides, esters, ethers), as well as in the autoxidation and combustion processes [12, 20]. In the case of wood photo-degradation process, alkoxy radicals are responsible for producing methanol (from the methoxyl groups present in lignin), formaldehyde and hydrogen (from the photo-dissociation of methanol), carbon monoxide (from carbonyl groups through photo-oxidation), and carbon dioxide (from carboxyl acid groups evidenced in wood by irradiation).

The first research studies were performed on wood and unbleached mechanical pulps and described the role of lignin and the effects of ambient oxygen, temperature and humidity [35–37]. The chemical changes in lignin associated with light-induced yellowing were evidenced, the reduction in methoxyl groups content being strongly related to the brightness decreasing. It is well-known that lignin presents a phenyl propane as basic unit (softwood species have methoxyl-phenyl propane units – namely guaiacyl propane units, while hardwood species contains an additional methoxyl group). Besides these, there are also present various reactive groups including carbonyls, carboxyls, and ethers [38–40].

As evidenced by early studies [41, 42], free radicals are not usually present in wood. A small amount of free radicals can result from wood surface activation in the presence of oxygen from air, this acting as a catalyst or promoter. Usually, these free radicals are phenoxy radicals resulted from oxidation of the phenyl type moieties from lignin component in wood [8, 43].

On the other hand, considering the significant UV absorption ability of lignin, it may also protect the cellulose component from photo-degradation process [43]. The depletion of the relatively hydrophobic lignin from the wood surfaces can occur during wood exposure to UV light action [21]. Given the interaction of wood and UV radiation which is mainly a surface process when UV light penetrates slightly wood [44], the generation of the free radical intermediates originating from lignin is the main promoter for the wood surface deterioration and discoloration [8, 12, 45]. The free radicals rapidly generate hydroperoxide type moieties in the presence of oxygen from surrounding atmosphere these further producing chromophore groups, namely carboxyl and conjugated carbonyl groups.

The occurrence of the photochemical reactions on the wood surfaces implies the absorption of an amount of energy by different chemical moieties, this energy having to be capable to disrupt a chemical bond [7]. The dissociation energies for many of carbon oxygen bonds usually found in lignin moieties are present in the UV radiation range (295–400 nm). The elevated temperature generates higher level of vibration energy. The interaction of these two effects may result in higher photo-degradation rate at 80 °C than at 30 °C, for example [46].

Some significant features of the photochemical reactions in wood were previously evidenced [9, 39] and briefly summarized [20]. Thus, significant colour changes occurs, these being determined by the chromophore groups formation through lignin degradation process under wood exposure to light having wavelength <350 nm. Discoloration (or photo-bleaching) process is observed when wood is exposed to light with wavelength value >400 nm. As consequence, the methoxyl groups content of lignin is reduced, while phenoxy radicals are readily formed from phenolic hydroxyl groups. The last mentioned intermediates generate o-quinonoid structures through demethylation reaction promoted by oxygen atmosphere [39]. Phenoxy radicals could be also involved in radical transfer reactions which may further confer stabilization to wood, as suggested by Kamoun et al. [47].

Several test methods have been developed using artificial light sources to provide accelerated weathering testing procedures and for comparison purposes when considering natural environmental weathering. Usually, all these methods imply the monitoring of the main features reflecting an ageing process which include mechanical properties and optical characteristics (roughness increase with evidence of crack formation, changes in colour and gloss). The selection of an artificial weathering method is frequently preferred due its shortened duration by comparison with a natural weathering test which instead provides more accurate and reproducible data. The durability of non-finished and finished wood products that will be used outdoors can be effectively evaluated through artificial weathering methods [4, 22, 30, 46, 48–52]. These valuable tests accelerate the effects of natural weathering up to 20 times as function of the established conditions for exposure which can be controlled and reproduced. Generally, the accelerated weathering tests envisage investigation of the effects exerted by UV light, humidity and temperature. Simulation of all factors causing natural weathering degradation including UV

light, temperature variations, wetting by water, discoloration by mould and stain fungi is not readily achievable under accelerated weathering testing conditions.

Photo-degradation of wood surfaces under UV radiation action is usually affected in outdoor conditions by other environmental factors including mainly humidity, temperature, visible light, and infrared radiation. The wavelength of the radiation can be known, its energy and intensity at the surface can be also determined by using UV-laser lamps [53, 54] instead of traditional UV lamps (xenon and mercury vapour lamps) as radiation sources during irradiation testing. In this case, the duration of accelerated weathering experiments can be significantly reduced.

An increased lifetime of wood is an essential prerequisite for sustainable outdoor applications (e.g. roofs, doors, windows type frames, bridge type structures built over rivers, roads, or railways). Wood presents a natural durability in terms of biodegradation, this feature being strongly related to the wood species (is higher in hardwoods than in softwoods) and mainly to the extractives content and composition [55]. This durability can be predicted by infrared spectroscopy [56, 57].

The lifetime of wood can be efficiently improved through biological control of wood resistance against fungal decay [58], and different treatments applied to wood [26] including thermal e.g. heating [59, 60] and chemical modification using anhydrides, acid chlorides, and silanes. The chemical routes include treatments such as acetylation [26, 27, 29, 61–63], succinylation [13], butyrylation [64], furfurylation [65], or silylation [66, 67].

Chemical modification of wood represents an effective manner to improve its weathering resistance and photostability [68, 69]. Effective and easily modification of wood can be achieved by using vinyl esters that can contribute to wood photostability and generates acetaldehyde as a desirable non-acidic by-product [70, 71]. Modification of wood using aromatic vinyl esters can also protect wood from photo-degradation [28], this protection being strongly related to the type of the ester used for wood treatment and the degree of modification (evidenced by weight gain values). It was concluded that wood protection from photo-degradation requires a more complete chemical modification of wood polymer constituents when comparing with the degree of modification demanded by achieving significant prerequisites such as wood dimensional stability and prevention of its biological degradation. In this context, a more feasible and effective way to improve the wood photostability implies use of aromatic compounds having a simple, non-branched structure and a low molecular weight that can modify wood by easily reacting with its polymer constituents when a high degree of substitution of accessible hydroxyl groups could be achieved [28]. Another promising way to improve wood photostability is conferred by use of polymeric polyester-type UV absorbers (UVA), produced by reaction of an epoxy-functionalized UV absorber (a benzophenone type compound with anhydrides maleic, phthalic, or succinic [72]). It was evidenced that the most effective UV absorber for wood photostability (by preserving the benzophenone group and hindering weight and tensile strength losses during accelerated weathering) was the polyester *Im* resulted from reaction of the epoxy-functionalized UV absorber with phthalic anhydride.

The most sensitive indicator that evidence occurrence of wood degradation process under UV light exposure is the colour change of wood [24, 45, 73–75]. The rapid colour differences evidenced after irradiation as primary consequences of the photo-oxidation phenomena can be useful for establishment a correlation between testing of accelerated and natural durability [76].

Chemical modification of wood (e.g. with succinic anhydride) may confer it more stability in colour under artificial light action comparatively with the non-modified wood, this feature being due to a slight increase in lignin stability under exposure to UV action [13]. Successive treatment stages (with succinic anhydride and epoxy functionalized soybean oil) provided protection of wood from photo-oxidation reactions under UV radiation exposure as related to the colour preservation, expressed by a reduced fading tendency [77]. As expected, lignin underwent significant photo-oxidation reactions, exhibited as increase of the redness tendency of wood surfaces. Nevertheless, the modified wood surface was protected by the coating layer consisting of epoxy functionalized soybean oil through a screening effect.

A promising way to reduce the rate of free radical formation and thereby minimize the occurrence of wood discoloration (photo-yellowing) was recently presented [66] and involves the silylation of the UV radiation sensitive groups at the wood surface (in air and at room temperature) in order to interfere with the photo-degradation process, the resulted photo-induced free radicals being determined using ESR spectroscopy.

Traditional methods applied to protect wood against biodegradation (process that may enhance susceptibility to further photo-degradation) involve chemicals which usually pose toxicological effects upon human health and environment [78–80]. Recently, alternative methods for wood protection against biodegradation were reviewed and presented with focus upon significant opportunities of using natural products as biocides and environmental biocompatible compounds [81]. Nevertheless, these organic biocides may be susceptible to photo-degradation [82] and have to be co-impregnated with protecting agents. A potential route to be efficiently applied for conversion of softwood species into self-antibacterial and sustainable wood materials (e.g. for decking and fencing purposes) was recently presented [83]. This novel process involve chemical attachment of quaternary ammonium compounds via a carbamate/urethane linkage to softwood (in this case, hemlock) using supercritical carbon dioxide. The resulted chemically modified softwood exhibited excellent antibacterial activity and enhanced dimensional stability.

Lignin is a photo-labile aromatic polymer component from wood structure which presents chromophore groups with great affinity to absorb UV radiation that mainly initiate further degradation process of wood and wood-based materials (e.g. wood/wood composites, wood/polymer composites) under solar light and artificial light exposure [5, 14, 15, 84–89]. Wood/polymer composites (usually coded as WPCs) are emerging hybrid materials comprising wood as filler, and thermoplastics as polymer matrix (polyethylene PE, polypropylene PP, polyvinylchloride PVC, polystyrene PS), produced through different processes (e.g. extrusion,

injection moulding) and presenting a better dimensional stability by comparison with the usual wood products. Incorporation of wood fibers within a polymer matrix has positive and significant advantages including possibility to use recycled raw materials with large volume and low cost, reduced energy and production costs, improved environmental behaviour (being environmental-friendly materials) and properties (mechanical: stiffness; physical: resistance against moisture, biological decay, UV radiation; thermal stability; easy processing ability; dimensional stability). The properties of WPCs (e.g. appearance, mechanical) are strongly dependent by the interaction between wood fibers and the polymer matrix, this interaction being improved by addition of coupling agents.

Exposure of wood/polymer composites to weathering in outdoor conditions [90] generates significant changes including colour with impact upon aesthetic appearance, and reduction in mechanical performance. These changes are the consequence of the surface chemistry changes including mainly oxidation processes occurred on the composites surfaces which affect crystallinity of the polymer matrix and cause degradation at the interface areas. Both components, wood and thermoplastic polymer undergo photo-degradation processes in the presence of water and UV radiation. These two factors act in a synergistic manner by surface erosion and increasing wettability, thus causing mechanical properties loss and reducing their lifetime. This synergism is more harmful than exposure of composites to UV radiation only [91]. Cellulose component from wood structure is the main responsible for water absorption through its hydroxyl groups and further causes wood fibers swelling on the composites surface with formation of more pores susceptible to allow UV light penetration. Under UV radiation exposure, the polymer matrix undergoes intense cracking processes.

A measure of the WPCs surface degradation is represented by oxidation that increases following weathering process. Photo-degradation disrupts molecular bonds with formation of the free radicals on the surface. These radicals interact through chain scission, generating shorter molecular chains with high mobility and susceptible to re-crystallization phenomena [92]. Changes in the chemical composition at the surface of WPCs can be investigated by Fourier transform infrared (FTIR) spectroscopy, with a simultaneous evaluation of the changes in the polymer matrix crystallinity.

During a prolonged exposure to UV radiation, significant colour changes occur with increasing carbonyl groups content and wood loss on the WPCs weathered surfaces [14]. Wood species, namely their lignin and wood extractives contents, are responsible for WPCs discoloration through photo-degradation during weathering process [8, 88, 93], expressed by oxidation of structures originated mainly from lignin (α -carbonyl, biphenyl, ring-conjugated double bond structures) with generation of carbonyl and carboxyl groups (as chromophoric groups). The photo-degradation of wood and wood/polymer composites can be attenuated by using different UV stabilizers, including UVA hydroxybenzophenones and hydroxybenzotriazoles; pigments (used in coatings; for WPCs are used titanium dioxide and carbon black), and hindered amine light stabilizers (HALS triazine-based and diester-based for WPCs), the last ones mentioned being applied

alone or in combination with bridged amines [94]. For a best UV protection, these UV stabilizers are usually combined, because UVA enable formation of the free radicals, while HALS compounds inhibit the photo-degradation reactions [95]. The addition of pigments and mineral fillers can represent an efficient method to improve the weathering properties of WPCs [96, 97], fact evidenced by enhancement of their color stability and moisture resistance especially in outdoor weathering. Usually, pigments, inorganic and organic types, are often added to inhibit the photo-degradation of polymer matrix in WPCs [98]. They are usually applied alone or in combination with other protective agents such as UVA in printing inks, paints, stains, and coatings [99, 100]. Addition of a low percentage of nano-sized UVA in coatings composition (below 5 %) contributes to improvement of wood characteristics including weathering performance, physico-mechanical and thermal properties [100-103]. Their efficiency is determined by a good dispersion, that's why water-based media are preferred in order to avoid coagulation of nano-sized UVA in paints, both in the wet and dry states. Titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles are widely used in paints and coatings to block harmful portions of the solar radiation and to reduce the rate of photo-degradation processes [100, 104].

The application of a maintenance coating is highly recommended when an extended life-time of protected wood materials is envisaged, mainly in outdoor exposure conditions which require a better performance and durability during weathering. Most coating systems have no ability to control the moisture content variations in the wood surfaces which significantly affect the long-term performance of both substrate (wood) and coating [105]. The durability of wood coating systems is expressed by reaching different types of limit states (e.g. micro cracks that are hardly visible) which require restoration [106]. A developed coating material of known and controlled rate of decomposition, based on poly (vinyl acetate) copolymer binder in combination with Fe^{2+} as redox catalyst, can be used as weathering indicator in artificial and natural (outdoor) exposure [107]. This weathering indicator is useful for comparison purposes, e.g. different locations as weathering intensity, artificial weathering devices, and time periods by monitoring significant weathering factors such as UV irradiation, humidity, precipitation. Further, it could indicate the necessity of a sustainable maintenance of coated wood surfaces in outdoor applications (e.g. constructions). The data obtained by using the weathering indicator can be combined in terms of time with the durability of wood coatings in order to reach a limit state [106, 108].

3 Conclusions

Wood is a renewable material that is produced through natural processes in forest ecosystems. Wood chemistry and structure are both strongly related to its degradability that is also influenced by the environmental conditions (humidity, temperature, UV radiation, pollutants). In order to fulfill the requirement of

sustainability, a well-established equilibrium between biosynthesis, transformation and degradation should exist. Modification of wood or its main polymer component, cellulose, is an effective way to improve its stability against biodegradation processes caused by different biological agents. This method can be chemical (e.g. acetylation) or physical (thermal treatment), protecting wood to some degree from biological degradation, with a positive effect on the lifetime of wood based materials. UV weathering, a process initiated primarily by the UV portion of the solar spectrum, causes photo-chemical degradation reactions on the wood surfaces. Knowledge of the chemical structure of wood polymer components and their interactions with UV radiation is essential for understanding the chemistry of UV photo-degradation of wood. Photo-chemical degradation of wood causes significant structural and color changes, lignin component being the most susceptible to de-polymerization reactions by which phenoxy radicals are generated as intermediates and further oxidized into colored chromophores (quinones). This pathway is well-known as the repeating phenoxy quinone redox cycle, by which under UV radiation, hydroquinones are oxidized to paraquinones which are further reduced to hydroquinones by the effect of hydroperoxy radicals. Chemical changes can be evidenced by FTIR spectroscopy. Effective treatments, e.g. UV photo-stabilizers, or surface coatings of wood products, e.g. paints, varnishes, stains or water repellents, may provide significant wood protection against weathering in long-term outdoor applications. The application of a maintenance coating is highly recommended when an extended life-time of protected wood materials is envisaged, mainly in outdoor exposure conditions which require a better performance and durability during weathering.

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